Perception of Low-Amplitude Haptic Stimuli when Biking

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ABSTRACT

Haptic stimulation in motion has been studied only little earlier. To provide guidance for designing haptic interfaces for mobile use we carried out an initial experiment using C-2 actuators. 16 participants attended in the experiment to find out whether there is a difference in perceiving low-amplitude vibrotactile stimuli when exposed to minimal and moderate physical exertion. A stationary bike was used to control the exertion. Four body locations (wrist, leg, chest and back), two stimulus durations (1000 ms and 2000 ms) and two motion conditions with the stationary bicycle (still and moderate pedaling) were applied. It was found that cycling had significant effect on both the perception accuracy and the reaction times with selected stimuli. Stimulus amplitudes used in this experiment can be used to help haptic design for mobile users.

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *Evaluation/methodology, Haptic I/O.*

General Terms

Performance, design, experimentation, human factors.

Keywords

Tactile feedback, perception, mobile user, biking.

1. INTRODUCTION

Using haptic feedback provides several benefits compared to other modalities for mobile users. First, haptics can provide private information in a nonintrusive way. Second, with haptics it is also possible to provide information in the ways where users do not have to interrupt their actions, while still getting the information they need when moving. Several factors affect the design of haptic feedback in mobile situations. These include, for example, optimal stimulus parameters and low power consumption.

There has been some previous work on using haptic cues to provide information for mobile users. Most of the work on haptics in human-technology interaction (HTI) has focused on prototype studies. In these studies a haptic prototype has been built and tested to answer special needs of a mobile user. Other approaches have studied how haptic components should be designed and how users recognize and distinguish different haptic stimuli.

A number of studies have described which parameters can be used to encode information using single vibrotactile actuators. For example, van Erp [6] studied acuity of perception of vibrotactile stimuli on several locations on the torso. Brewster and his colleagues have done research on how to design and recognize information decoded into tactile icons (i.e., tactons) [1][3]. Often questions about perception of the stimuli are solved simply by providing large enough amplitudes to be perceived, so that research on distinguishing varying stimuli could be carried out. Another way is to create a tactile display by linking two or more actuators together to provide more versatile information for the user. (e.g., Piateski and Jones [4]).

Tactually enhanced user interfaces have also been created and tested with mobile users. Brewster *et al.* [2] proved that users benefit from vibrotactile cues in text entry tasks in distracting use situations. Van Veen and van Erp [8] showed that tactile information can be provided for the airplane pilots to reduce their visual information overload. They also observed that reasonable G-load did not affect the perception of the vibrotactile stimuli but decreased performance was reported close to the individual G-tolerance levels. Thus, based on this, it can be assumed that a similar phenomenon could also be found on the effects of the movement in perception. Tactile displays could be beneficial also in the sports, where haptic information can be used to maintain high performance more easily and with less effort, as van Erp *et al.* [7] proved in their study.

Van Erp's guidelines [5] based on psychophysical studies on vibrotactile perception in the context of HTI suggest that optimal stimuli would be long-lasting 200-250 Hz vibration on glabrous skin with fixed surroundings around the vibrating element. Van Erp concludes that threshold for the sensation of the haptic feedback varies widely between individuals and by age.

Optimal haptic stimulation would be perceived both when moving and when staying still. Furthermore, optimized feedbacks would also be more comfortable for the users willing to avoid unnecessarily high-amplitude feedbacks. Although it would be beneficial to have a rough limit for the lowest amplitudes to use in the field of haptic design, there is little if any research done on perception limits of the haptic feedback for the needs of mobile users in the field of HTI. Probably this is due to the fact that several variables are effective when sensing tactile stimuli. One factor is that it is difficult to measure those actual forces in between the contact point of skin and the actuator. Even skin properties vary individually a lot. For example, the amount of body fat and temperature do affect the sensitivity of tactile

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receptors. Furthermore, the technology as such can provide within stimulus variation which further creates difficulties for exact threshold measurements. For these reasons our aim was in general to find out whether and how much moderate physical exertion affects the perception of the vibrotactile stimulation.

2. EXPERIMENT

2.1 Participants

16 voluntary participants (3 females and 13 males) participated in the experiment (mean age 32 years, range 20-50 years). All of the participants were right-handed by their own report. One participant was rejected from the analysis due to missing all of the stimuli presented in both experiment conditions. Thus, the results are based on data from 15 participants.

2.2 Apparatus

In the experiment the participants were provided with vibrotactile feedback to four body locations (i.e., wrist, leg, chest, and back). Two motion conditions were used: sitting still on a stationary bicycle (i.e., immobile condition) and keep up a moderate bicycling pace (i.e., mobile condition). A mouse with a button was attached in the middle of the handlebars to provide user input. Data from the perceived stimuli was collected with the reaction times measured from stimulus onset to the response of a button push. The stationary bicycle used in the experiment was a Tunturi E40 ergometer[1].

Figure 1: Experimental setup.

Four actuators were attached in the non-dominant side of the body. Locations of the actuators were wrist (i.e., hairy side of the wrist, in the watch location), leg (i.e., above the knee between knee joint and quadriceps), chest (i.e., in the side of the thorax) and back (i.e., under the shoulder blade). Actuators in the leg and wrist were attached with an elastic Velcro strap and in the chest and the back attached under the partially elastic transmitter belt of the heart rate monitor (see Figure 1 for the actuator attachments). During the experiment participants listened to pink noise via a hearing protector headset to avoid responses based on the sound produced by the haptic actuators.

Vibrotactile stimuli in the experiment were provided by Engineering Acoustics Inc. C-2 actuators[2] driven through a sound card with WAV audio files. Stimuli were amplified with a StageLine STA 1508 eight-channel amplifier[3] which provides possibilities to accurately modify output amplitudes for separate channels. The stimuli were played and data collected with a C++ software ran on a powerful Windows XP PC. The system clock of the computer was used for timing the stimuli and the collected data. The software collected data from all the responses and reaction times calculated from the stimulus onset to the button down event. If participant pushed the button later than 2000 ms after the stimulus offset, the answer was considered to be late and not taken to the analysis.

2.3 Pilot Testing

The stimuli used in the experiment were selected through extensive pilot testing. The same participants that attended to the pilot tests were not used in the experiment. After the first pilot runs it was found that there is a need to look after appropriate stimuli amplitudes through extensive pilot testing, because exertion appeared not to have any effect on the perception. At first the idea was to use the same amplitudes in all locations and to compare the detection between different locations. However, it was soon found that the stimuli should be designed location-specific due to the differences in perception sensitivity. Because we were interested in whether the exertion affects the perception, we decided to adjust the stimulus amplitudes step by step closer to the perception limits of the participants to see whether the performance decreases or not.

The first pilot tests were carried out with one of the four actuators attached in the palm. However, the location was reported uncomfortable by the participants and the actuator was relocated in the back. The amplitude values for each location were varied from the maximum of the homogenous 250 mV to location-specific values of 20, 170, 40, and 40 mV for wrist, leg, chest, and back, respectively. It was also confirmed during pilot testing that there is variation between and even within the participants; the same participant could one day perceive all the stimuli in one location and another day miss all the same stimuli in the same location under the same clothing and environmental conditions.

2.4 Stimuli

Stimuli used in the experiment were 250 Hz sine wave mono WAV files with 44.1 kHz sample frequency. Stimulus durations used were 1000 ms and 2000 ms. Amplitudes varied based on actuator location and were selected for each location to be barely noticeable for the participants. These amplitudes were selected through extensive pilot testing so that on average the participants could perceive most of the stimuli in an immobile condition but not all of them in a mobile condition. Reason for this was that in pilot testing it seemed that the effect of the movement fades away if the stimuli were more intense than the stimuli close to the average perception limit. Thus, with higher amplitudes participants perceived all the stimuli, both in immobile and mobile conditions.

Amplitudes used in the experiment are shown in Figure 2 and accelerometer values for each location are presented in Table 1. The acceleration data was collected with DimensionEngineering DE-ACCM3D +/- 3g tri-axis analog accelerometer. The g values presented here are peak-to-peak accelerations analyzed from the 24800 samples gathered during 2500 ms intervals (10000

[1] http://www.tunturi.com/

[2] http://www.eaiinfo.com/

[3] http://www.monacor.de/

samples/s). During the measurement the C-2 actuator was placed firmly in a cut slot inside a matchbox filled with Bostik Blue-Tack reusable adhesive to eliminate unwanted resonance. Only the data from the z-axis was gathered for the analysis.

Table 1: Amplitudes of the stimuli.

Amplitudes	Back	Wrist	Chest	Leg
V	0.04	0.02	0.04	0.17
G	0.1760	0.1171	0.1760	0.4838
V/g	0.2273	0.1708	0.2273	0.3514

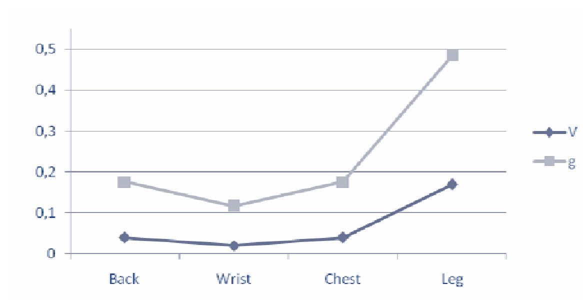

Figure 2: Stimuli amplitudes in volts and g-values measured by accelerometer.

During the experiment the participants were provided with a total of 40 stimuli, ten to each location. For each location a half of the stimuli were 1000 ms long and the other half were 2000 ms long. The stimuli were presented in the blocks to one location at a time. The order of the blocks was randomized between the participants by using Latin square table. Interstimulus interval varied randomly between 5000 ms and 10000 ms. 1000 ms and 2000 ms stimuli were presented randomly within each block.

2.5 Procedure

First, the participants were instructed to what they should do during the experiment and a background questionnaire was collected. The experiment was run in two blocks, each of which took approximately five minutes to complete. At first immobile condition was carried out to ensure that participants were not physically stressed as immobile condition was used as a reference to the exertion condition. In the immobile condition participants were sitting on the stationary bicycle and in the mobile condition they were cycling with a 50 W resistance. Participants were instructed to keep the pedaling rate between 45-55 rpm. They were also told not to interrupt the experiment if they failed to keep up the pace. Eventually, none of the participants failed to keep the requested pedaling rate during the experiment.

Participants were instructed to respond as fast as possible by pushing a button every time they felt a stimulus, even if they noticed it "late", for example, after the stimulus offset. They were asked to use their dominant hand to push the button. Thereafter, actuators were attached in their non-dominant side. The mouse was attached in the middle of the handle bars of the bicycle and in the handle bar there was a mark, over which participant should keep the thumb during the experiment.

After the instructions a block was put under the pedal of the bicycle on the participant's non-dominant side to prevent pedal movement during immobile condition (see Figure 1) and actuators were attached to the participant. Stimuli were introduced before the experiment by providing stimulation to all locations simultaneously for a couple of seconds. This gave participants a reference point for what to expect to feel during the experiment. Then the immobile condition was carried out. During the immobile condition the participant held the pedal towards the wooden block and sat still while receiving stimuli. After the immobile condition the participant was asked to step off the bike and stretch out a bit, while experiment setup was prepared for the mobile condition. After a short break participant was asked to sit on the bike again and mobile condition was carried out.

2.6 Data Analysis

Repeated measures analysis of variance (ANOVA) was used for statistical analysis. Pairwise Bonferroni corrected *t*-tests were used for post hoc tests. Stimulus locations were analyzed separately because the stimulus amplitudes varied through the locations.

3. RESULTS

3.1 Perception Rates

Mean perception rates and standard error of the means (SEMs) are presented in Figure 3. A two-way 2 × 2 (motion condition × stimulus duration) ANOVA showed a statistically significant main effect of the motion condition for the back $F(1, 14) = 8.2$, $p < 0.05$, the wrist $F(1, 14) = 7.0$, $p < 0.05$, and the leg $F(1, 14) = 9.5$, $p < 0.01$. The main effect of the stimulus duration was significant for the chest $F(1, 14) = 13.1$, $p < 0.01$. The interaction of the main effects was not statistically significant for any location. Post hoc pairwise comparisons for all locations individually showed that the participants reacted significantly more accurately in immobile than in mobile motion condition to the stimulation in the back $MD = 21.3$, $p < 0.05$, the wrist $MD = 20.7$, $p < 0.05$, and the leg $MD = 37.3$, $p < 0.01$. To the stimulation in the chest the participants reacted significantly more accurately to 2000 ms than to 1000 ms stimuli $MD = 10.0$, $p < 0.01$.

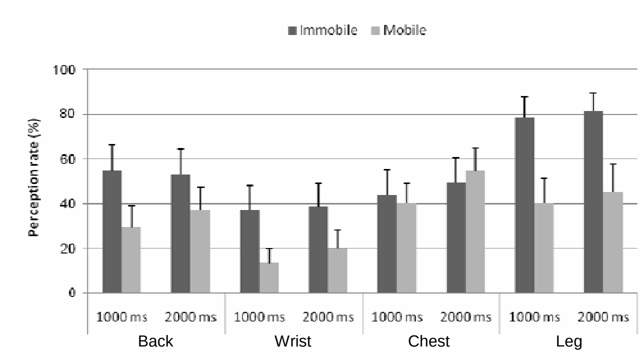

Figure 3: Mean ratings and SEMs for perception rates of the stimuli by motion condition, stimulus duration, and location.

3.2 Reaction Times

Mean reaction times and SEMs are presented in Figure 4. A two-way 2 × 2 (motion condition × stimulus duration) ANOVA showed a statistically significant main effect of the motion condition for the back $F(1, 14) = 21.9$, $p < 0.001$. The main effect of the stimulus duration and the interaction of the main effects were not significant for this location. A statistically significant interaction effect of the motion condition and stimulus duration was found for the wrist $F(1, 14) = 5.5$, $p < 0.05$, the chest $F(1, 14) = 6.6$, $p < 0.05$, and the leg $F(1, 14) = 14.2$, $p < 0.01$. As it can be seen from Figure 4 the interactions were due to the fact that the participants reacted faster to the 2000 ms stimuli than to the 1000 ms stimuli in immobile condition and the other way around in mobile condition. Thus, two separate one-way ANOVAs were performed for wrist, chest and leg locations. These analyses revealed a significant effect of the motion condition for the wrist $F(1, 14) = 18.1$, $p < 0.001$ and the chest $F(1, 14) = 26.1$, $p < 0.001$, but not for the leg. The effect of the stimulus duration was not statistically significant for any of the three locations. Post hoc pairwise comparisons for all locations individually showed that participants reacted significantly faster in immobile than in mobile motion condition for the stimulation in the back $MD = 289.1$, $p < 0.001$, the wrist $MD = 344.9$, $p < 0.001$, and the chest $MD = 553.0$, $p < 0.001$.

Figure 4: Mean ratings and SEMs for reaction times to the stimuli by motion condition, stimulus duration, and location.

4. DISCUSSION AND SUMMARY

We found that lower amplitudes than the ones commonly used today can be applicable for haptic feedback, and thus, there are possibilities to lower power consumption by optimizing stimuli amplitudes. van Veen and van Erp [8] found that the G-load on the fighter pilot did not have an effect on the recognition of the stimuli until being close to the G-tolerance limits of the participants. It seems that a same kind of phenomenon can be found with physical exertion close to the perception limits of the participants.

Our results showed that movement had statistically significant deteriorating effects on the perception and reaction times of tactile stimulation when stimulus amplitudes were close to the perception limits of the participants. However, in any of the conditions the perception did not totally drop to zero. For reaction times it is noteworthy that in immobile condition the 2000 ms stimuli were reacted faster than 1000 ms stimuli. These results can have different implications for designing haptic stimulation guidelines for mobile and immobile applications. Therefore, when providing clearly noticeable vibrotactile cues, which can be perceived when not moving, the cues should be perceived also when moving with low physical exertion. However, when providing very low-level stimulation, motion condition of the user has to be taken into account and haptic stimulation has to be modified based on the user's level of exertion.

We found that the wrist needed less than 0.12 g vibratory stimuli to be barely perceived, while the chest and the back required 50% (0.18 g) and the leg 300% (0.48 g) higher amplitudes (see Table 1). Exceeding these values with a fair tolerance should be better perceived by both immobile and mobile users when using vibrotactile actuators attached to the skin, like the C-2 actuators used in this experiment.

Stimulus duration did not have a significant effect on the the reaction times or perception rates for other locations than the chest. Thus, it seems that 1000 ms stimuli are long enough to be perceived. Based on our experiment we cannot, however, argue that stimulus duration does not have an effect at all, but more research is required with longer and shorter stimulus durations.

To summarize, the results showed that movement had an effect on the perception rates and reaction times in most locations studied when low level amplitudes were used. Because of this, we suggest using slightly higher amplitudes for mobile users than immobile users when using very low amplitude haptic stimulation.

5. ACKNOWLEDGMENTS

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